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TECHNIQUES FOR ANALYSIS AND VALIDATION OF UNSTEADY BLAST WAVE PROPAGATION

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13. ABSTRACT *(Maximum 200 words)*
Several best practices were developed for performing blast wave propagation analysis using Fluent, a commercial computational fluid dynamics (CFD) package. The purpose of this was to be able to quickly simulate the blast field around large caliber gun systems. These best practices include the areas of: determining initial grid quality and characteristics, solver selection and discretization scheme, solver stability on initial start-up, unsteady grid adaption, and solver space domain selection. In addition, validation and verification are discussed. Techniques for post-processing unsteady blast data are discussed.

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BACKGROUND

Analyzing blast wave propagation presents several unique computational fluid dynamics (CFD) requirements. Over the past year and a half, Benet Laboratories has developed techniques to better model blast wave propagation from gun tubes using CFD. Several lessons have been learned about how to apply CFD. The purpose of this report is to discuss the methods used.

The 120-mm gun used on current tanks, such as the M1A1 Abrams, produces very high levels of "kick" or gun recoil. These loads are imparted to the vehicle through the gun mount and recoil system. The Abrams is a 60 to 70 ton vehicle, and because of its large mass, it can absorb these high impulse loads. However, because of its size, vehicles like the Abrams are not air transportable by C-130 aircraft. Typically, tanks are transported by ship and over land, resulting in a long deployment time. The Army is currently looking at much lighter vehicles, in the 16- to 18-ton range, that are air transportable on C-130 aircraft. This would make quick global deployment achievable. As such, the 120-mm gun needs to be mounted on a much lighter vehicle. These lighter vehicles are not able to withstand the impulse loads produced by standard guns. As a result, devices are required to reduce the gun recoil.

A common device used on large caliber guns to reduce recoil is the muzzle brake. Muzzle brakes take some of the flow exiting the gun tube after the projectile exits the barrel and turns that flow laterally. As a result, the recoil produced by the gun tube is reduced. However, as the flow is deflected near the vehicle, the resulting blast wave produced by the high-pressure gases exiting the gun tube becomes much stronger. At the vehicle, blast levels become very large and can potentially damage the vehicle structure, or the human body, particularly the ear. The Army is looking for ways to reduce recoil without increasing blast pressure levels. As a result, analysis tools are required with CFD being used to model blast wave propagation from gun tubes in order to predict blast pressure.

MODELING GOALS

Two values need to be determined by CFD in order to determine safe sound levels for troops in and around gun tubes. These are peak overpressure and B-duration. A sample pressure versus time trace, taken from the military standard for noise limits, MIL-STD-1474D (ref 1), is shown in Figure 1. As can be seen, the main blast wave produces the maximum, or "peak overpressure." The B-duration is the length of time from the arrival of the blast wave until the high frequency noise amplitude decreases to less than 10% of the peak overpressure. The peak overpressure is primarily a fluid mechanics phenomenon that can be modeled with CFD, whereas the B-duration is primarily acoustic in nature. Current CFD efforts are focused primarily on determining peak overpressure levels.

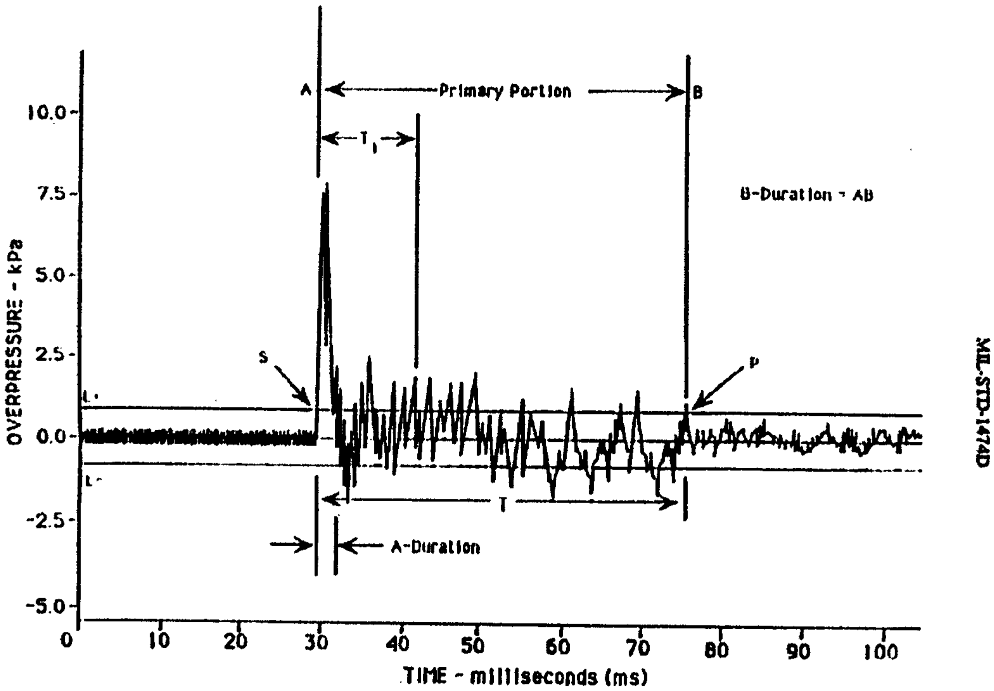

Figure 1. Pressure trace from typical gun tube firing showing peak overpressure, A-duration, and B-duration.

Because the flow-field is so large and it is important to determine blast wave strengths up to 100 meters from the gun tube, dynamic adaption of the grid is critical in order to minimize solution time. An example of dynamic adaption is shown in Figure 2. Dynamic adaption methodology was first developed using Fluent 6.0 with execute commands. Using execute commands provided significant flexibility in using the full suite of static adaption capability within Fluent 6.0, including gradients, iso-surfaces, combines, limits, etc. However, because Fluent 6.0 was not designed to adapt frequently, stability issues were often encountered. Much of what was learned from these initial development efforts was used to develop and test Fluent 6.1's new dynamic adaption capability. The dynamic adaption capability in Fluent 6.1 was presented by Benet Laboratories at the Fluent 2002 User's Group Meeting. Fluent 6.1's new dynamic adaption capability allows for more efficient and stable unsteady adaption, but with a limited sub-group of Fluent's static grid adaption tools.

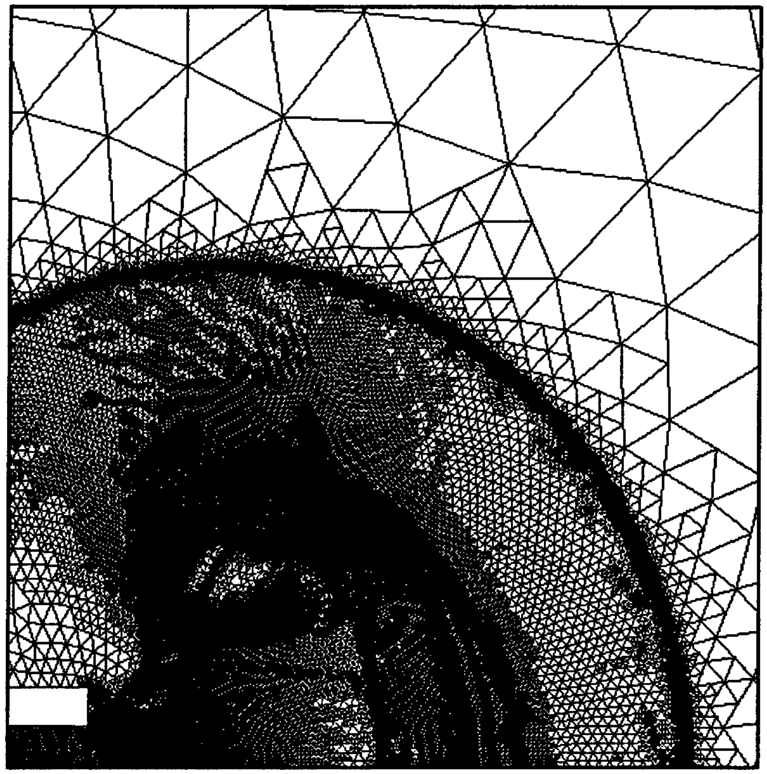

Figure 2. Adapted grid from 7.62-mm NATO G-3 study.

BEST PRACTICES

Several best practices were developed for performing blast wave propagation analysis. The first critical factor is the initial grid quality and characteristics. Initial grids are developed using Gambit's sizing functions. As a result, grids are made to grow from small cells near the muzzle of the gun to large cells far away. Thus, far-field cells near corners in geometry can become highly skewed unless care is taken in creating sizing functions properly. Highly skewed cells will create solution problems, even if they are in the far field. Also, cells near areas with strong pressure gradients around corners may not be dense enough or of sufficient quality to capture the aggressive flow physics. This can often lead to solutions that can become unstable. In addition, when adaption occurs, large jumps in cell size can cause stability problems. A poor grid quality in an area that is adapted with large changes in cell size will only compound problems.

To create initial grids using Gambit, fixed-sizing functions are used. The sizing function for the initial grid needs to take into account how adaption will occur and what the final adapted grid sizes will be. This is important from a solution efficiency perspective. The minimum cell size needs to be determined by the geometry refinement, and the maximum cell size should not be more than 100 to 1000 times the minimum in order to maintain solution stability. Maximum cell size needs to take into account whether adaption is going to be performed and to what level. A lower mid-level maximum cell size would be used when adaption is not going to be used. This will produce a relatively coarse far-field grid on which a quick non-adapting solution can be applied. If adaption is to be used, larger cells in the far field can be used, with the anticipation that large cells will be reduced in size several levels. Sizing-function growth rates should be between 1.1 and 1.5. The minimum cell size must not be too small because the time-step will be inadequate for an efficient solution. Also, one needs to consider how the grid will grow when considering maximum cell sizes.

A second important issue with blast wave simulation is solver selection and discretization scheme. The best solver for blast wave problems is the coupled-explicit solver with explicit time-stepping. This combination usually produces quicker solution times than the coupled implicit solver with implicit time-stepping. In addition, first-order upwind flow discretization seems to be more stable than the second-order upwind flow discretization. Often it is difficult to complete a second-order solution. Second-order is better for refining shock structures on courser grids, however first-order solutions are more achievable. Therefore, a first-order solution with a higher level of grid adaption seems to be the best alternative.

A third issue is solver stability on initial start-up of a blast problem. To run simulations of gun blast, an initial condition of pressure, temperature, and velocity is patched into the gun tube just upstream of the muzzle or the muzzle brake. The solution is then initiated, allowing the flow to expand out of the gun tube. This produces very strong shocks or discontinuities in the flow-field. As a result, unphysical velocities can be seen on start-up. This then affects the total temperature and pressures. It appears that changing limits (static temperature, static pressure, or positivity rate limit), changing solver discretization (first-order or second-order), changing time-step (Courant number), or changing the solver formulation (using couple-explicit with explicit time-stepping or using coupled-implicit with implicit time-stepping) has little effect on correcting these unphysical velocities on solution start-up. However, these unphysical velocities tend to dissipate after a couple thousand time iterations, especially when running first-order discretization. The unphysical velocity gradients tend to be worse for second-order discretization. As a result, using second-order discretization can sometimes lead to solutions that may relate to this problem. When running the couple-explicit solver with explicit time-stepping, it is import to limit the Courant number to about 0.85 for first-order and to about 0.3 to 0.5 for second-order solutions. This is because the time-step is controlled by the Courant number. These limits on the Courant number ensure that a flow particle will not move through the smallest cell in the flow domain for first-order solutions and will accommodate curvature changes within the smallest cell for second-order solutions.

A fourth important issue is unsteady grid adaption. In some cases, it is better to start with a medium-level grid and run the solution without adaption. Because adaption adds overhead to a solution, it should only be used when necessary. A solution achieved on a mid-level, far-field grid without adaption can achieve pressure values within ±25% with a rather large grid in the far field (20- to 100-cm cell size). This is often good for an initial guess and for the purposes of testing the problem setup.

Using dynamic adaption tends to improve the peak overpressure determination that is critical to certifying a gun system to MIL-STD-1474D (ref 1). Using more adaption tends to increase the peak overpressure and sharpen the front side of the blast. It is important when performing adaption to select the correct adaption function and to select the proper adaption controls. Typically, a gradient of density using the gradient adaption method is best suited for resolving blast waves and shocks. A scaled normalization of the gradient levels with a refine threshold of 0.7 and a coarsen threshold of 0.3 works well for resolving near-field shock structures; however, a lower refine level is required for weaker shocks that propagate toward the tank or vehicle.

It is important to use both the minimum cell size and refinement level together to control the adaption process. The minimum cell size is used to control the time-step of the solution. In an explicit solution, the cell size and Courant number dictate the time-step. Having cells that are too small will cause excessively long solution times due to time-steps that can be as low as 1e-8 to 1e-10 seconds. Minimum cell size can also control the cell count in the near-field, where cells are not refine-level limited. Setting the refinement level can control cell size and cell count in the far field. In the far field, the initial grid is quite large and the grid will be refinement-level limited. No volume weighting is used.

A fifth important issue when doing blast wave analysis is the solver space domain. Two-dimensional solutions tend to produce higher blast wave pressures because two-dimensional blast waves dissipate as r^2. Real systems tend to produce blast waves that dissipate as r^3. The results can be orders-of- magnitude different from one another in the far field as a result. Because of this effect, caution needs to be used. The axisymmetric and three-dimensional space domains offer better estimates of blast wave pressures.

VERIFICATION AND VALIDATION

Verification and validation is an important issue with this type of problem. Verification can be performed using an exact solution explosion problem, such as the Sedov explosion problem (ref 2). The Sedov explosion problem has an exact solution for both a cylindrical two-dimensional case and a spherical three-dimensional case. The CFD results can be compared to the exact solutions of velocity, pressure, and density at any time in the solution in order to validate solution accuracy. This is good for determining the most efficient way to achieve a given level of accuracy. In addition to code verification, the code is validated both qualitatively and quantitatively. The CFD-generated contour plots of density were compared to experimental shadowgraph images of the 7.62-mm NATO G-3 Rifle (ref 3). The results of this study were presented at the Fluent UGM 2002 and at the 41st AIAA Aerospace Sciences Meeting (ref 4). In addition, more recently, results from CFD solutions were compared to experimental pressure-time traces of real gun systems.

POST-PROCESSING

Post-processing of unsteady data is also important. Ensight is used to perform this analysis. Execute commands are used to produce scalar, velocity, and geometry files every 200 to 2000 iterations. Ensight has the capability to make movie images of data files and perform extensive unsteady data visualization. Fluent 6.1.x will have the capability to write unsteady Ensight files from the command menus in the future for the couple-explicit solver with explicit time-stepping. Fluent 6.1.18 currently has this capability for the implicit time-stepping solvers. In addition, pressure versus time is recorded using the surface monitor capability within Fluent.

CONCLUSIONS

Progress has been made using Fluent to model blast waves. Work will continue with Fluent to find better adaption techniques and methods to make the code more efficient for solving blast problems. A large-scale unsteady adaption problem has not been performed using Fluent as yet. Most work has been primarily two-dimensional and axisymmetric. Work will continue in the future using Fluent to model blast, and with advances in the code and solution techniques, large three-dimensional blast solutions may be achievable in a week's time with parallel processing. In the past, large three-dimensional blast solutions would not have been attempted.

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